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Exoplanet plenitude

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The main aim of the present paper is to give a brief overview of the revolution in exoplanet discoveries which started about two decades ago and the new concepts and perspectives that these observational findings have brought about. The level of the text is simple, as deemed suitable for reading by young scientists with different levels of expertise. The paper is organized in the following sections: 1) Historical background. 2) Basic concepts and definitions of what is a planet. 3) Observational evidence of planetary diversity and the theoretical pathways to explain what we see. 4) Future research directions.

Key words: stars: brown dwarfs, stars: formation, planets and satellites: formation

HISTORICAL BACKGROUND

On 24 August 2006, at the end of its 26th General Assembly held in Prague, the International Astronomical Union (IAU) passed a resolution on the definition of the term *"planet in the Solar System"* which made headlines around the world because it demoted Pluto to the lesser category of dwarf planets. This decision was adopted after a voting result of 237-137, which implied that only a minority of the IAU members actually casted a vote. The discovery of a few objects beyond the orbit of Neptune with sizes comparable to Pluto (see e. g. [17]) prompted the IAU to react. However, as noted by Nobel prize winner Brian Schmidt in a public talk at the 220th meeting of the American Astronomical Society in Anchorage on June 12, 2012, the decision on Pluto is still controversial. The statement of Prof. Schmidt on this sensitive issue was "Once a planet, always a planet".

Even though there is a clear definition, albeit controversial it may be, for what a planet is in the Solar System, it is not straightforward to extrapolate it to exoplanets. The masses of planets in the Solar System span about 4 orders of magnitude from Jupiter to Mercury. This is one order of magnitude more than the mass range for stars. Hence, the term planet refers to a broad class of objects that includes a wide range of properties.

Jupiter has mass of $1.89 \cdot 10^{27}$ kg = 317.83 Earth masses, which may seem as a lot, but in fact it is a little less than 1/1000th of the mass of the Sun. Just below 1/10th of a solar mass, electron degeneracy sets in as the dominant pressure in the interior and creates a kind of object named a brown dwarf (BD) that behaves differently than stars do [30, 34]. Contrary to stars, BDs are not known to die and produce interstellar ashes; they rather keep cooling off, slowly shrinking and shining faintly forever. There is no BD known in the Solar System, but other solar-type stars are endowed with brown dwarf companions (see e. g. [59]). Nevertheless, most of the BDs we know are single. They have been revealed mainly by wide-area surveys (see e. g. [58]) and by pencil beam deep surveys (see e. g. [39]). Very recently cross-matching of large public catalogues using the Virtual Observatory tools have demonstrated that an increase in the efficiency in the identification of BDs is possible [1].

The last two decades of the 20th century gave us the discoveries of GD 165B, a BD companion to a white dwarf [8]; a planetary system around the pulsar PSR1257+12 [82]; PPL1 and Teide 1, bona fide BD members in the Pleiades star cluster [61, 71]; Gl229B, a BD companion to a nearby star [51, 55], and close-in substellar-mass objects around solar-type main-sequence stars [36, 50, 44]. These findings have galvanized planetary and stellar research by providing the first examples of sub-stellar-mass objects that do not exist in the Solar System. They have also brought about much debate about the meaning of the term "planet" and how to distinguish it from the term "brown dwarf" [5, 14, 69, 73].

ON THE DEFINITION OF "PLANET"

By analogy with the Solar System, an unambiguous planet is an object that resembles one of the eight major planets that orbit the Sun. However, it is clear that such a narrow definition of what a planet is has not been adopted in the astronomical literature. A pressing question is: how much is it useful and reasonable to stretch the definition of what a planet is? Clearly, there is no consensus in the community because drawing a hard boundary for what a planet is, would include objects that are the favorites of some astronomers, but it may also exclude objects that are the favorites of others if the definition is carefully crafted. For example, the planet

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definition proposed by the IAU Working Group on Extrasolar Planets[1] would include most of the planets discovered by the radial velocity technique, but it would exclude those discovered around pulsars by the timing method, and also the free-floating (also called nomads, rogue or unbound) planets found by microlensing [74] and cluster planets found by deep direct imaging in very young open clusters such as Sigma Orionis and the Trapezium [42, 57, 83] and follow-up spectroscopy [16, 47].

In the dim light of the still incipient understanding of exoplanets, a simple, convenient and clear approach to a planet definition is not coming forward yet. Several new kinds of objects have been discovered in the last two decades that have some planetary attributes and that do not exist in the Solar System Table 1. This diversity reminds once again the ancient plenitude principle, discussed by great philosophers dating back to Socrates and Plato, and including Giordano Bruno and Immanuel Kant [28, 40], and recognized as a general unification theme in natural phenomena. A definition of what is a planet should not fail to pay due respect to the diversity of planets, which has been an astonishing revelation of scientific endeavor in the last two decades, and constitutes a modern verification of the age-old principle of plenitude.

Taking into account the currently available information on the topics of BDs and exoplanets, an updated definition of planet is offered here. It goes as follows: *A planet is an object that has a mass large enough to have a gravitationally-dominated internal structure, i.e. nearly spherical shape, but not large enough to sustain any kind of stable nuclear fusion over long periods of time. The word planet can be used for any kind of celestial object that is, has been or will be a planet.*

By this definition, a planet can be found free-floating in space, unbound to a more massive object; and a planet can also be gravitationally bound to multiple stars, single stars, stellar remnants, failed stars such as BDs or recycled stars such as blue stragglers. A planet can have smaller objects orbiting it that are called satellites. When the mass ratio between a planet and a satellite is close to unity, the system may be called a double planet.

From the cosmogony point of view, there can be many different pathways to form a planet, and this casts some doubt that planet formation could be either an adequate physical quantity or a useful observational criterion to define what a planet is. In practice, it is convenient to adopt a planet definition that heavily relies on the mass of the object because the mass can be either measured directly or it has an impact on observable quantities such as surface gravity. For solar composition the boundary BDs and planets is determined by deuterium fusion, which ceases to be stable at around 13 Jupiter masses [18, 19]. Just as the lithium test has effectively been applied as a tool to distinguish between very low-mass stars and BDs [6, 43, 46, 62, 72], the deuterium test has been proposed to distinguish between BDs and planets [9] but it has not been carried out yet because it is observationally very challenging. This important observational test may have to wait for the advent of the 30-meter class generation of ground-based telescopes such as the European Extremely Large Telescope or the American Thirty Meter Telescope. Particularly promising targets are nearby late-T dwarfs with effective temperatures around 500 K that appear to have peculiar properties indicative of young age and planetary mass, such as for example ULAS J1335+11 [37].

PLANETARY PLENITUDE AND FORMATION PATHWAYS

The observational evidence for protoplanetary disks around very young stars is overwhelming. One of the most spectacular examples are the pictures of photoevaporating disks obtained with the Hubble Space Telescope near O-type stars in the Orion star-formation complex [53]. Another impressive example is the disk seen around the young (10 Myr) and nearby (19.5 pc) β Pic star [66, 75] which hosts a massive planet (8 M_{Jup}) at a semimajor axis of about 12 AU [35]. Statistical studies of the infrared excess among the stellar populations of star-forming regions and young open clusters indicate that most stars are born with surrounding circumstellar disks that dissipate with a timescale of about 10 Myr [4, 80]. However, while it is clear that planets form in circumstellar disks around newly formed stars, it is not clear at all what are the properties of those planets. None of the techniques that are widely used for exoplanet detection works very well for very young stars. So far the technique that has provided more exoplanet detections at very young ages is direct imaging from space or using adaptive optics from the ground [20, 45], but it is limited to semi-major axis larger than a few AU and only has sensitivity to planets more massive than Jupiter.

In the near future a promising technique to identify exoplanets around newly formed stars is accelerometry at near-infrared wavelengths using novel calibration techniques such as new cells that combine a variety of gas mixtures [2, 78, 79] or laser frequency combs [54]. The pros and cons of different calibration techniques are discussed in [49]. So far infrared radial velocity has not revealed any new planet, but it has been useful to rule out a giant planet around one of the nearest T Tauri stars (TW Hya) which was claimed by a study made at optical wavelengths [31]. Infrared radial velocities have also been used to reject the presence of a planet around the nearby ultracool dwarf VB10 [7, 65]. A multi-band approach

[1] `http://www.dtm.ciw.edu/boss/iauindex.html`

to improve the RV precision in active stars has been advocated by [12].

When all the known exoplanets are plotted in mass versus separation diagram, the result is a scatter diagram (see Fig. 1). Exoplanets are everywhere except where technical limitations preclude detectability. Such a wide range of properties indicate the presence of multi-parametric complexity. The simple picture of planet formation as core accretion of planetesimals in a disk around a single star has been shattered by the extravaganza of exoplanet discoveries. The solar nebula theory where the Solar System stems out of a flattened disk of dust and gas rotating around the Sun has been for over 200 years, and still seems to be for some, the main conceptual pillar of theories of planet formation [32, 33].

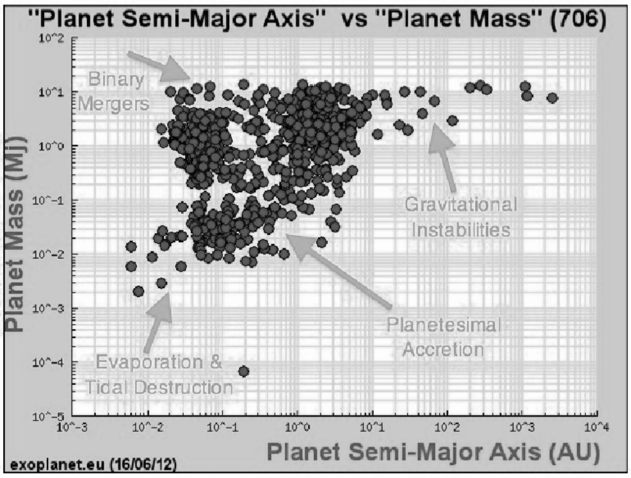

Fig. 1: Distribution of masses in Jovian units with respect to semi-major axis in AU for 706 exoplanets from the Extrasolar Planets Encyclopedia. Different planet formation pathways that are likely to populate different parts of the diagram are labeled.

It is now widely recognized that planets do not necessarily stay where they were formed. Tidal interactions of planets with their stars, interactions of planets with the disks and gravitational scattering of planets due to other planets, BDs or stars in multiple systems can result in significant orbital evolution of newly born planets, and even produce free-floating planets via ejection. The large eccentricities of many exoplanets are thought to indicate the influence of planet-planet scattering [77] and the Kozai mechanism [81]. Evidence for planet ejection may come from observational studies of extremely young multiple systems such as the protobinary TMR-1 in the Taurus-Auriga star-formation region [63, 76]. Both planets and brown dwarfs are likely to form in massive disks [70], making it hard to distinguish these two types of objects using some sort of cosmogonical criteria.

FUTURE DIRECTIONS IN EXOPLANETARY RESEARCH

An obvious focal point of future research on exoplanets is the detailed characterization of the myriad of known systems, both the stellar hosts and the planets themselves. Approved space missions by ESA (GAIA and Euclid) and NASA (JWST) will bring significant advances in our understanding of exoplanets and their stars. In analogy with the brown dwarfs for which three new spectral classes have been developed (L, T and Y), it has been suggested to classify hot Jupiters as pL and pM class [26]. It will be worthwhile to develop such analogies even further and use brown dwarfs as benchmarks to develop the tools needed for deriving fundamental parameters of exoplanets such as chemical composition, effective temperature, rotational broadening and surface gravity. A step in this direction is the analysis of high-resolution near-infrared spectra of late-M [22] and T dwarfs [21] using model atmospheres. Prospects for spectroscopic characterization of exoplanet atmospheres from space and from the ground are indeed very promising [3] and may be coupled with developments in high performance coronography [29].

A somewhat more controversial issue is whether significant investments should be made in the direction of finding Earth twins around solar-type stars. The widely held views in the scientific community, that the Earth does not occupy a special place in the Universe, may not support the idea that a major investment of public funds should be devoted to an antropocentric strategy in exoplanet research. Moreover, it is clearly more cost effective to detect and characterize habitable Earth-sized planets around small primaries such as very low-mass stars, BDs and white dwarfs [10, 11, 56]. Nevertheless, the urge to find exoplanets as similar as possible to the Earth around stars as similar as possible to the Sun is very strong because of its connection to Earth-centered branches of science such as Biology and Geology.

The existence of regular spacings in the orbits of planets in the Solar System and among exoplanetary systems is becoming well documented [13, 41]. This long range order in planetary systems was first recognized as the Titius-Bode law. It is likely a feature stemming out from the origins of the systems which remains to be fully accounted for.

Consideration of planet formation and evolution in binary systems opens new research perspectives. From the theoretical point of view, the formation of close-in planets in the excretion disks of merging binaries should be explored in detail [48]. It is very exciting to witness the detection of circumbinary planets after over a decade of unsuccessful attempts [23, 24, 25]). More efforts devoted to revealing planets around post-binary evolution stars, such as blue stragglers and R Corona Borealis stars, and stellar remnants will shed light on the processes of planet formation and evolution in binary systems. In the solar vicinity blue and red stragglers have been identified which are likely the result of the coalescense of stellar binaries [60, 67]. About 30 of them have been identified within 30 pc of the Sun [27, 64], and it would be very worthwhile to increase their numbers.

The ubiquity of planets around stars implies that they become excellent contenders to explain some mysteries in stellar evolution. For example, HERSCHEL/HIFI observations of water vapor in AGB stars [52] are not well understood. An intriguing possibility that deserves further scrutiny is that the water detected in those stars could be coming from water-rich planets that spiral in toward the star during the AGB phase. Some of the planets swallowed by the stars during the course of post-main sequence evolution may have an impact on the stellar mass loss rate and rotation velocity [38]. Orbiting substellar-mass companions have been posited as a plausible ingredient to model the non-axisymmetrical structure of planetary nebulae [68]. A possible link between lithium depletion, rotational history and the presence of exoplanets has been explored for solar-type main-sequence stars [15].

Two decades after the discoveries of the first unambiguous specimens, it has become very clear that BDs and exoplanets are here to stay. They have provided a link between different scientific communities such as the geologists, the planetary scientists and the stellar astrophysicists, and in the future they are likely to foster much more interdisciplinary research.

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Table 1: Exoplanets that do not have analogues in the Solar System. It been compiled using the following online catalogues: The Extrasolar Planets Encyclopaedia (http://www.exoplanet.eu/); TEPCat: catalogue of physical properties of transiting planetary systems (http://www.astro.keele.ac.uk/~jkt/tepcat/).

Planetary Kind	Mass Range	Age Range	Metallicity Range	Known Number
Free Floating Planets	0.5 – 13 M_{Jup}	1–10 Gyr	Solar	a few dozens
Cluster Planets	3 – 13 M_{Jup}	1–10 Myr	Solar	a few dozens
Wide-orbit Planets (a>50) AU	6 – 13 M_{Jup}	1 – 100 Myr	Solar	7
Close-in Planets (a<0.1) AU	0.2 M_{Earth} – 8 M_{Jup}	10 Myr – 10 Gyr	0.3 – 3 × Solar	153
Super-Jupiter Planets	2 – 13 M_{Jup}	1 Myr - 10 Gyr	0.3 – 3 × Solar	213
Super-Earth Planets	1.5 – 10 M_{Earth}	1 – 10 Gyr	0.5 – 3 × Solar	55
Pulsar Planets	0.02 M_{Earth} – 2.5 M_{Jup}	1–12 Gyr	unknown	5
White Dwarf Planets	0.37 – 7.7 M_{Jup}	1–12 Gyr	unknown	11

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